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Considerations for Modeling Vessel-Generated Currents and Bed Shear Stresses

by E. Allen Hammack and J. N. Tate

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) contains a description of the new vessel effects capabilities in the hydrodynamic code ADaptive Hydrology/Hydraulics (ADH). Guidelines for creating initial mesh refinement along a sailing line are included as well as determining the values for parameters that control automatic mesh adaption during a simulation. ADH has also been extended to include calculations of bed shear stresses induced by flat-bottomed vessels. These shear stresses can be used in modeling sediment resuspension.

BACKGROUND/INTRODUCTION: The effects of a vessel on a flow field have been shown to contribute to bank erosion in navigation channels as well as sediment suspension within these channels. Modeling such effects has been performed using fixed-mesh codes and methods. These tools require large start-up time, user knowledge and experience, and computation times. The setup and run times are so large that, for many projects, they become prohibitive to the project. These computational issues have been alleviated using ADH, an adaptive-mesh flow solver. (Stockstill and Berger 1999, 2001; Stockstill et al. 1995)

The shallow-water equations have been modified to include vessel effects and capture the low-frequency flow characteristics. ADH allows the user to develop a coarse mesh to define the geometry of a flow field and have the mesh adapt itself during a simulation based on the flow conditions. This improvement is particularly beneficial in modeling the vessel effects within a flow field because the flow is complex around the vessel and this complex flow region moves throughout the flow domain as the vessel moves. The mesh is refined near the vessel automatically and regions of the mesh far from the vessel are not refined, thus reducing the required computational time.

SAILING LINE: The sailing line defines a vessel's path through the flow field and is defined as a set of line segments and/or arcs. The transition from one segment to the next should not have any sudden, large turns. Similarly, the radius of any arc sections of the sailing line should be large. Using the bathymetry data for a project site as a guide, the sailing line can be placed within the navigation channel. The sailing line may begin outside the mesh boundaries, which may be advantageous in situations where multiple vessels are modeled.

MESH CONSIDERATIONS: The initial mesh, also referred to as the coarse mesh, should only be as refined as necessary to capture the geometry (bathymetry and shoreline). The vessel geometry must also be considered in areas along the sailing line for the coarse mesh. The two-dimensional (2-D) mesh near the vessel is described in terms of lateral and longitudinal element sizes. Longitudinal means along a vessel's sailing line, and lateral means normal to a vessel's sailing line. After a convergence study was conducted, two elements completely within the

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vessel footprint were suggested for sufficient lateral refinement. The aspect ratio, the element length divided by the element width, of the elements within the vessel footprint should be about three or less. Previous studies have indicated that an element length of one-third of the vessel length is sufficient. The recommended initial resolution near a vessel is shown in Figure 1. The elements near the sailing line should be right triangles because the pressure-head contours from a simulation show a vessel footprint reflective of the vessel shape.

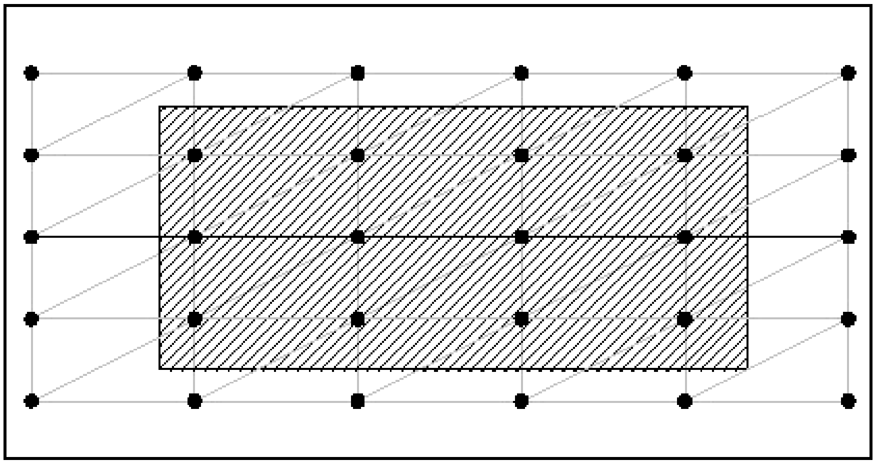

Figure 1. Recommended initial mesh resolution in the vicinity of vessel.

MESH REFINEMENT: Two user-defined parameters, the refinement tolerance and the maximum number of adaption levels, are used to control automatic mesh refinement (Berger and Lee 2005). The refinement tolerance value acts as a "trigger" value to determine which elements will be refined. The refinement tolerance is compared to the residual calculated for each element. If the residual is larger than the refinement tolerance, the element will be refined; otherwise, no adaption occurs. This tolerance is used to scale the residual values calculated for each element during a simulation. An initial simulation should be run with the refinement tolerance set to 1.0 to have a data set containing the actual residual values. Using the values in the error (*_err.dat) file, a mesh refinement tolerance for subsequent simulations can be chosen. With the error file loaded into the Surface-Water Modeling System (SMS), select several nodes near the sailing line but away from the vessel. The average of those error values should be used as the refinement tolerance. This value is set as the refinement tolerance for a simulation with the "MP SRT" card in the boundary condition (*.bc) file. The average error value is the final value in the "MP SRT" card. Using this approach on a test case yielded the adapted mesh shown in Figure 2.

The upper picture shows the outline of the vessel (the bold rectangle) with the initial mesh. The lower picture shows the vessel outline with the adapted mesh. The refinement is only near the vessel, which results in a large computational advantage from the adaption.

A mesh convergence study was performed to determine the maximum number of refinement levels required. Using a refinement tolerance found with the previously described method, the maximum number of adaption levels was increased from zero (for no adaption) until the velocity solution did not change for subsequent refinement levels. A plot of the convergence at a location in the mesh is shown in Figure 3.

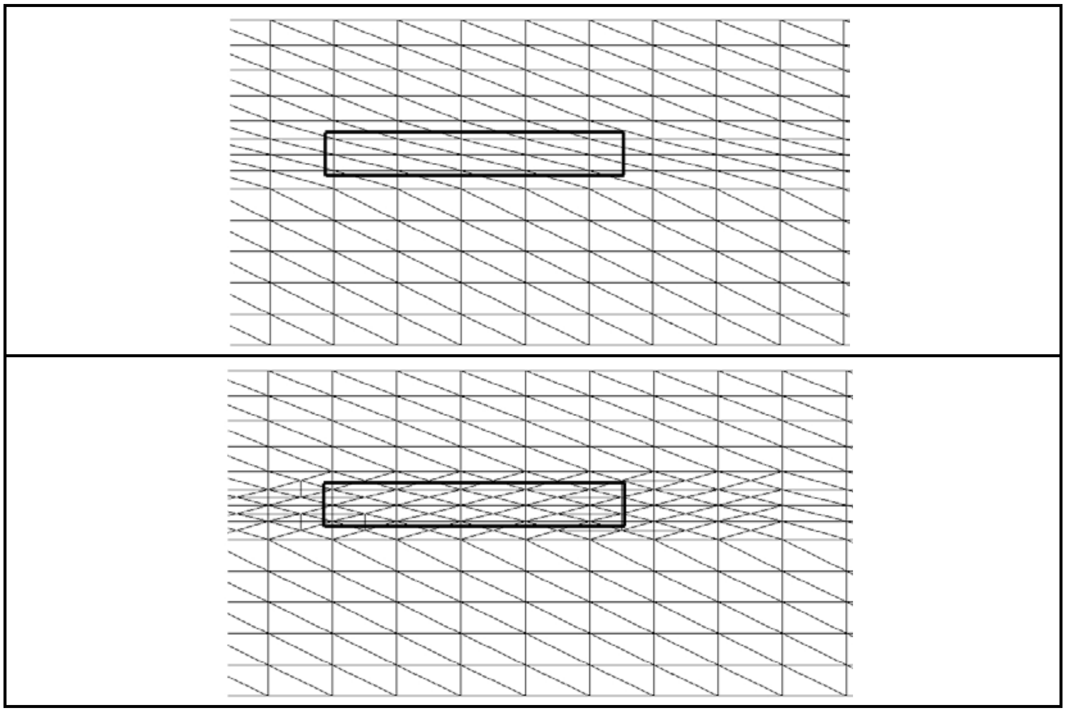

Figure 2. Mesh adaption around vessel.

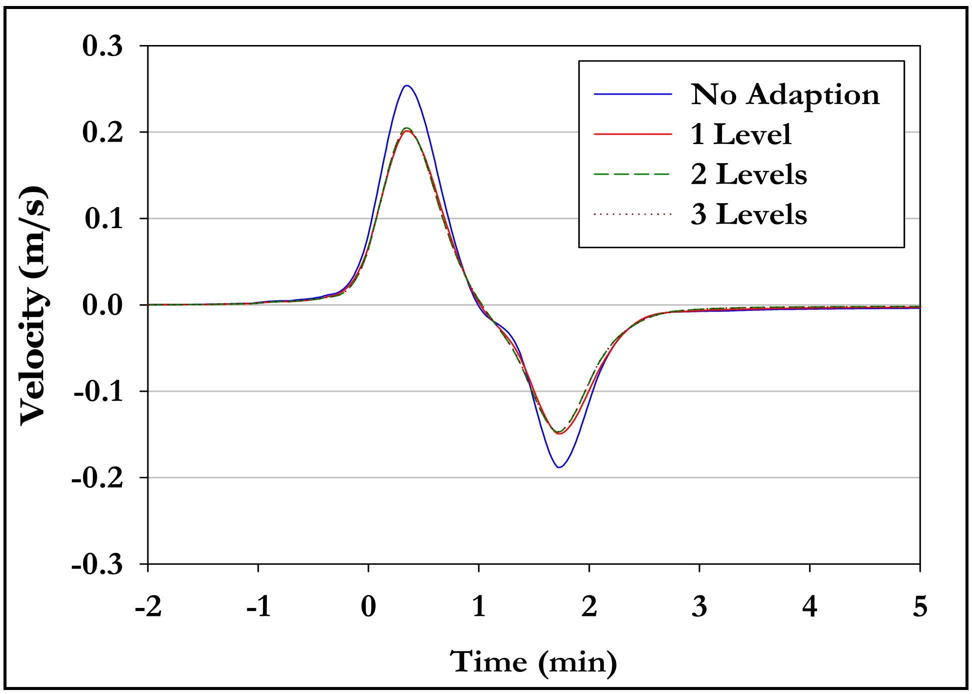

Figure 3. Velocity plot showing mesh convergence.

There is no change from the velocity solution using two levels of adaption and three levels of adaption. Therefore, only two levels of adaption are required for mesh convergence. The maximum level of adaption levels is set in the boundary condition file with the “MP ML” card.

TIME-STEP: The time-step should be set such that the vessel moves a distance of one element length per time-step. Moving at least one element length per time-step moves the vessel through the flow field smoothly. Figure 4 shows how the vessel should advance from one time-step to the next.

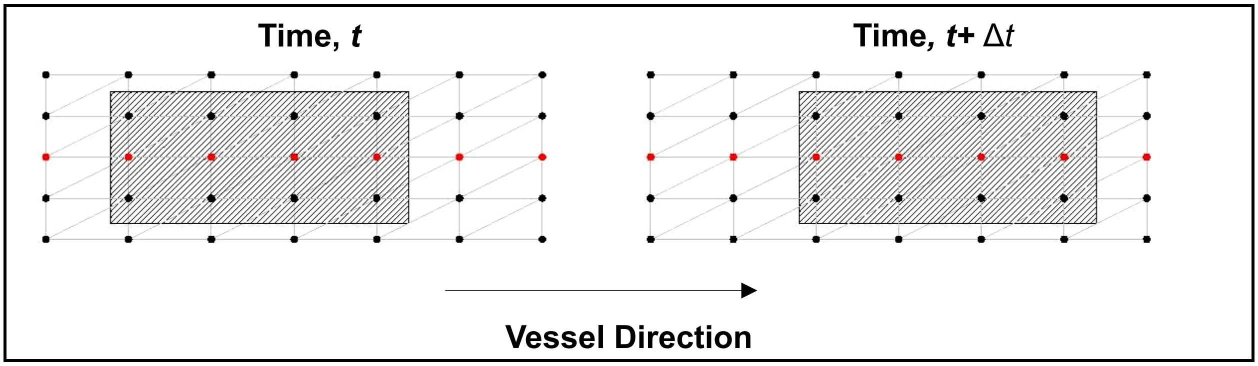

Figure 4. Vessel movement per time-step.

VESSEL DEFINITION: The term “vessel” can refer to either a single ship or barge or to an entire barge train. The vessel geometry and the sailing line information are defined in the boat (*.bt) file. The necessary propeller information used to calculate the vessel-induced bed shear stresses, which is discussed in later sections, is also contained in the boat file. The format of information that should be included in the boat file may change as ADH is enhanced. The most up-to-date boat file information can be found at *http://adh.usace.army.mil/*.

MODEL AND FIELD DATA COMPARISON: A simulation was run using the flow conditions of a section of the Illinois Waterway near Kampsville, IL (Bhowmik et al. 1993). The vessel modeled is a 3-barge-wide by 4-barge-long barge train. Figure 5 shows the ADH and field velocity data at one location in the channel. The ADH results compare well to the low-frequency field data in both the longitudinal and transverse directions. The low-frequency velocity behavior is the most significant contributor to the total force acting on vessels.

MULTIPLE VESSELS: ADH vessel simulations can be performed on single as well as multiple vessels. There is no limit to the number of vessels that can be simulated. However, a few issues should be remembered when developing a multiple vessel simulation.

In a typical waterway, the vessels travel in the same channel. If a vessel’s footprint overlaps that of another, the maximum draft at each node in the mesh is used to compute the pressure field. Figure 6 shows the depth contours generated by two vessels of the same size and draft moving toward each other. At the point where the two vessels collide (second image from bottom), the draft does not increase even though the vessel footprints clearly overlap. While this is not physically correct, the flow solution away from the vessels is correct. By allowing the vessels to pass through one another, the setup time for simulations is greatly reduced because fewer sailing lines are required and the user will not have to calculate the time when two vessels will pass one another. This technique is especially useful when only the far-field flow effects are of interest.

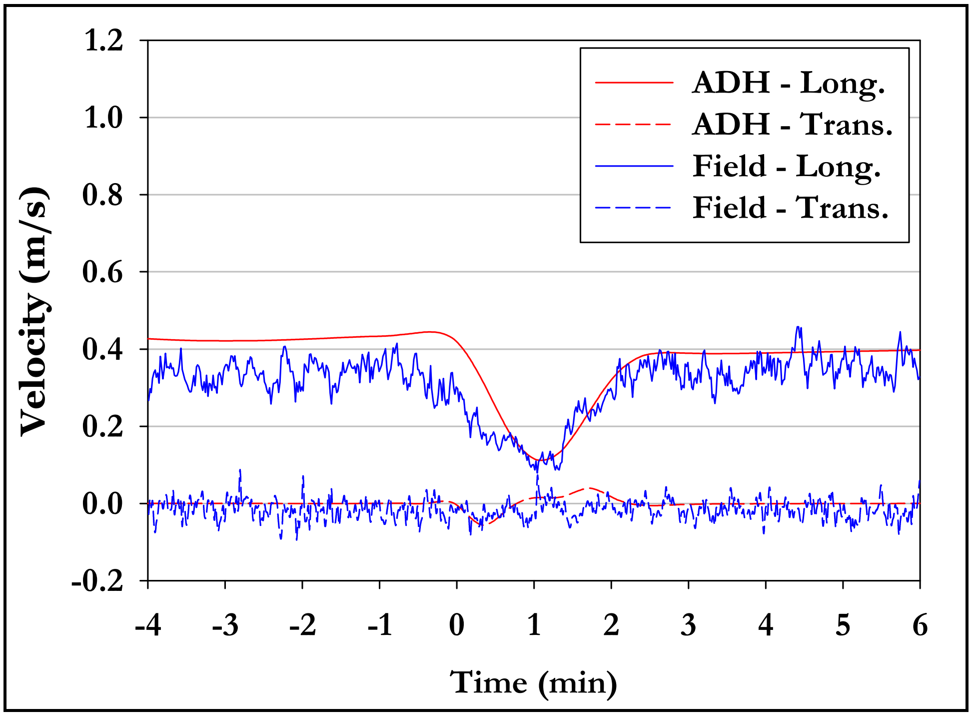

Figure 5. Velocity comparison of ADH results and field data.

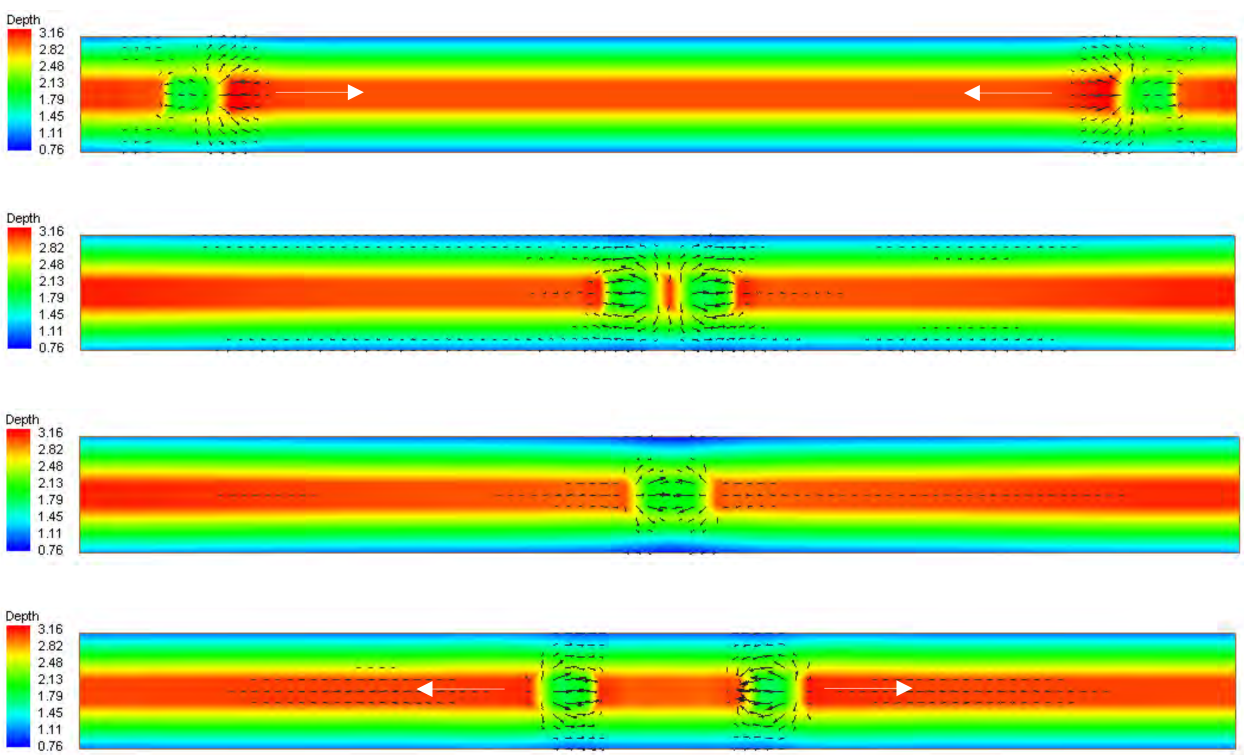

Figure 6. Passing vessels of the same size and draft in a straight flume.

When simulating multiple vessels, their paths will likely enter and leave the model domain at various times. However, including the entire vessel path in the meshed domain is not necessary. A simple method to have the vessels enter the model domain at different times is to start them at coordinates outside the mesh with velocities set so that they reach a given location in the domain at the desired time. As with any type of modeling, the vessels should start and end their paths at locations beyond the area of interest in the model, so no boundary effects interfere with the model results.

All vessels start moving at time zero of the simulation, and all vessels stop once one vessel reaches the end of its sailing line. A short line segment should be added to each vessel's sailing line that should stop within the flow field while other vessels continue to move. This vessel should slow to a small velocity ($\sim 1.0 \times 10^{-8}$) along this segment. Adding this segment defines a path for the vessel to move, which allows the other vessels to continue moving through the channel.

The drafts and vessel-generated velocities are included in the depth (*_dep.dat) and velocity (*_vel.dat) output files. The sailing line for each vessel is referenced to a time of zero, so if the beginning time of a simulation is changed, a vessel's location will be changed accordingly. This allows for simulations to be hot-started without having to make changes to the vessel definition file (*.bt). Figure 7 is a plot of the velocity contours taken from a multiple-vessel simulation of the Houston Ship Channel in southeast Texas. This channel sees about 50 vessels per day moving through the channel along various sailing lines (Tate et al. 2008).

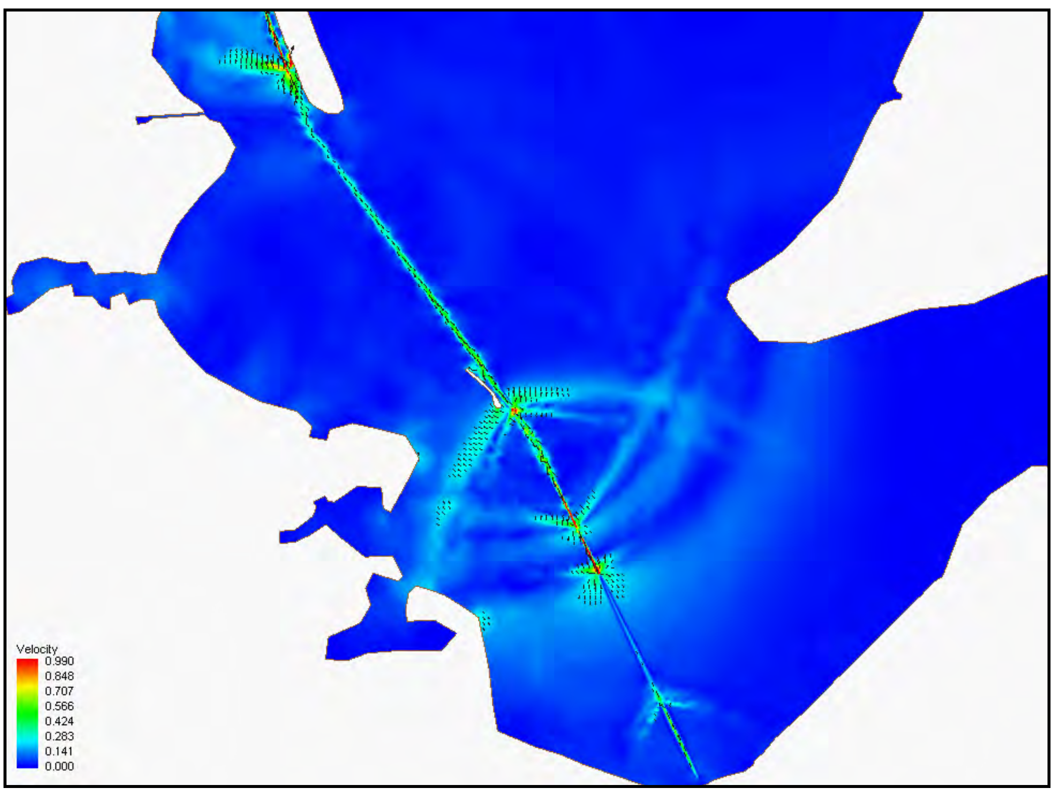

Figure 7. Velocity contours for five vessels traveling the Houston Ship Channel.

VESSEL-INDUCED BED SHEAR STRESSES: Empirical relations developed by Maynord (2000) have been incorporated into ADH to calculate the bed shear stresses induced by the vessel bow and propeller of flat-bottomed vessels. These relations require such inputs as the propeller diameter, the propeller spacing, towboat length, and the type of nozzle used on the propeller. The shear stress results using these relations give localized shear stress behavior at the vessel's bow and stern. Simulations where the vessel-induced bed shear stress is simulated must be performed in SI units. ADH records the vessel-induced bed shear stresses in a *_str.dat file in units of dynes/cm^2. An example of these contours is given in Figure 8. Note how the bed shear stresses induced by the propeller are much larger than those induced by the bow.

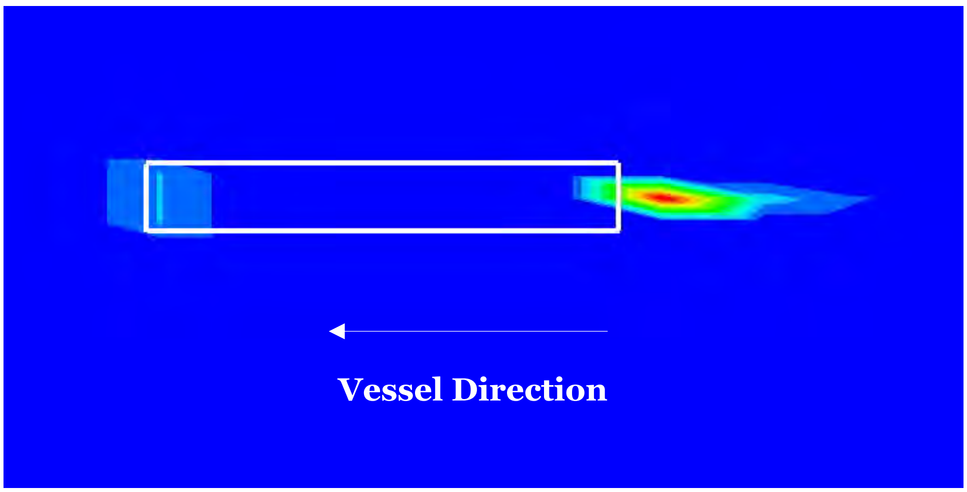

Figure 8. Bed shear stress contours and their location relative to vessel.

In future work, the vessel-induced shear stress on the bed due to the bow and propeller will be incorporated into the flow shear stress such that the sediment transport calculations will include these effects as well. Currently the sediment transport model only sees the shear stresses due to the flow, which is affected by the vessel motion.

ADDITIONAL INFORMATION: For additional information about this CHETN, contact E. Allen Hammack, Coastal and Hydraulics Laboratory (CHL), U.S. Army Research and Development Center (ERDC), 3909 Halls Ferry Road, Vicksburg, MS 39180 (at 601-634-3628, or Allen.Hammack@usace.army.mil). This effort was funded through the Navigation Systems Research Program. Program Manager is James E. Clausner, ERDC-CHL, at 601-634-2009 or James.E.Clausner@usace.army.mil. This CHETN should be cited as follows:

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